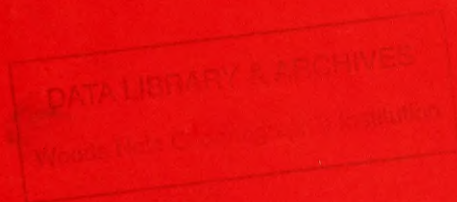# U. S. Army
Coastal Engineering
Research Center

A MULTI-PURPOSE
DATA ACQUISITION SYSTEM
FOR INSTRUMENTATION OF
THE NEARSHORE ENVIRONMENT

TECHNICAL MEMORANDUM NO. 21
AUGUST, 1967

DEPARTMENT OF THE ARMY
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A MULTI-PURPOSE
DATA ACQUISITION SYSTEM
FOR INSTRUMENTATION OF
THE NEARSHORE ENVIRONMENT

by

W. A. Koontz and D. L. Inman

U.S. ARMY

COASTAL ENGINEERING RESEARCH CENTER

ABSTRACT

Most energy from ocean waves and tides is ultimately transmitted
to the coastal periphery or nearshore zone. The dissipation of this
energy creates a complex environment characterized by intense inter-
actions between waves, currents, and sediments. A data acquisition
system, using digital techniques, has been designed and used in the
laboratory and field; it provides instantaneous-synoptic measurements
of the nearshore environment. Using modern computer techniques, the
system can efficiently acquire and analyze a tremendous volume of data.
Special sensors of the system include: a digital wave gage with self-
contained logic circuitry; a vibrating-wire transducer to measure
pressures on the bottom; a Savonius current meter; and a photography
technique for estimating the density of suspended sediments.

FOREWORD

A data acquisition system such as this one will be of great value
to coastal engineers. It could make possible a more accurate evaluation
of wave characteristics, littoral currents, littoral transport rates,
and their various interactions.

The paper was prepared at Scripps Institute of Oceanography, La
Jolla, California under contract with the Coastal Engineering Research
Center. The authors are Wayne A. Koontz, an electronic engineer, and
Professor Douglas L. Inman, both of Scripps.

At the present time, J. M. Caldwell is Acting Director of the
Coastal Engineering Research Center.

NOTE: Comments on this publication are invited. Discussion will be
published in the next issue of the CERC Bulletin.

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A MULTI-PURPOSE DATA ACQUISITION SYSTEM FOR INSTRUMENTATION
OF THE NEARSHORE ENVIRONMENT

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Section I.   INTRODUCTION

Most energy from ocean waves and tides is ultimately transmitted to the ocean periphery. Within the ocean periphery or nearshore zone, the energy is dissipated in various ways including reflection, generation of turbulence and longshore currents, transportation of sediment, and the formation of other kinds of waves. Some energy appears to become "trapped" against the coast in the form of edge waves and shelf seiche, thus leading to an increase in the energy level at the coast.

The many forms of energy flux and the high rates of energy dissipation near the surf zone cause the nearshore environment to be complex and one of intense interaction among waves, currents, and sediments. Understanding the processes in the nearshore environment requires a careful assessment of the amounts of energy in the various kinds of wave motion; determination of the mechanics of interaction of waves, currents, and sediments, as well as the careful evaluation of the rates of energy transfer into the formation of turbulence and heat and into the longshore transport of water and sediment. It seems likely that assessment of the energy in the various modes of wave motion can only be accomplished by instantaneous-synoptic measurements in and near the surf zone from a grid or array of sensors. In the simplest form the sensors would all be of the same kind (e.g., pressure, water level, etc.). The array should have both on-offshore and longshore components, with spacings between sensors that are of the order of one-quarter wave length. An array is necessary because measurements at one or two points cannot give direction of energy transport, nor distinguish between phenomena having similar frequencies but different modes (i.e., swell vs. edge waves; standing vs. progressive waves). Understanding the mechanics of interaction and transport also requires instantaneous-synoptic measurements from a number of sensors. However, in this case, the sensors are likely to be of different kinds and their array of smaller dimensions, say, the thickness of a boundary layer or the orbital diameter of a water particle trajectory. A typical investigation might include the simultaneous measurements of water velocity at several elevations, suspended sediment concentration at several points, and the water level and pressure field of the traveling wave.

It is interesting to note that laboratory and model studies of nearshore phenomena require the same kinds and numbers of instantaneous-synoptic measurements as the field studies, differing only in the scale of the sensor array and the period of the sampling interval.

Efficient handling of the large volume of data acquired from an array of sensors can be accomplished only by modern computer techniques. Computer programs, such as "BOMM" (Bullard, Oglebay, Munk, and Miller, 1966)*, enable complex time series to be rapidly manipulated and printed-out in the basic form of power spectra and cross-spectra. Such presentations allow the investigator to determine the principal energy modes in a given wave type and the correlation between these modes and those of associated phenomena.

The above considerations led to the design of a multi-purpose data acquisition system for field and laboratory instrumentation of the nearshore environment. The design of the data acquisition system (DAS) and some of its special sensors, together with a few of the field and laboratory uses, are described in the following sections.

Section II. ELECTRONIC COMPONENTS

The data acquisition system was designed to accept signals from a variety of instruments, convert these signals to useful data and record these data in forms amenable for processing by an electronic computer. The acquisition system was constructed of solid-state logic components on printed circuit boards. Recent production techniques have made it possible to obtain these boards as "off-the-shelf" items in most of the needed configurations. The acquisition system also has an instantaneous analog print-out on a paper chart so that channels can be monitored before and during recording to give visual indication of sensor performance. Also, the binary data entered on the magnetic tape can be step-scanned on visual lights mounted on the panel to ensure that correct sensor output is printed on the tape. Experience indicates that analog monitoring and visual display of tape entry are valuable assets to a data acquisition system.

Two portable racks serve to mount the entire system (Figure 1). One rack houses the electronic logic equipment and associated power regulators. The other rack contains recording equipment and storage batteries. The batteries are held by a pivoted carrier which maintains an upright position at all times. When being transported, the racks are tilted backward on their axles and rolled on rubber tires similar to the action of two-wheeled handcarts. The portable equipment racks are 52 inches high, 29 inches wide, and 24 inches deep. These are over-all dimensions, including the wheels and the lifting ring mounted on top. The logic equipment rack weighs 120 pounds and the power supply, with storage batteries, weighs 145 pounds. Power for the equipment may be obtained from the storage batteries or from a 60-cycle power line.

Neoprene-jacketed, 250-foot four-conductor cables connect remote sensors to the DAS. Mated underwater connectors are molded to the ends and may be coupled for operation at greater distances. Shorter cables are used in the laboratory, but otherwise the installation of the system is the same there as in the field (Figure 2).

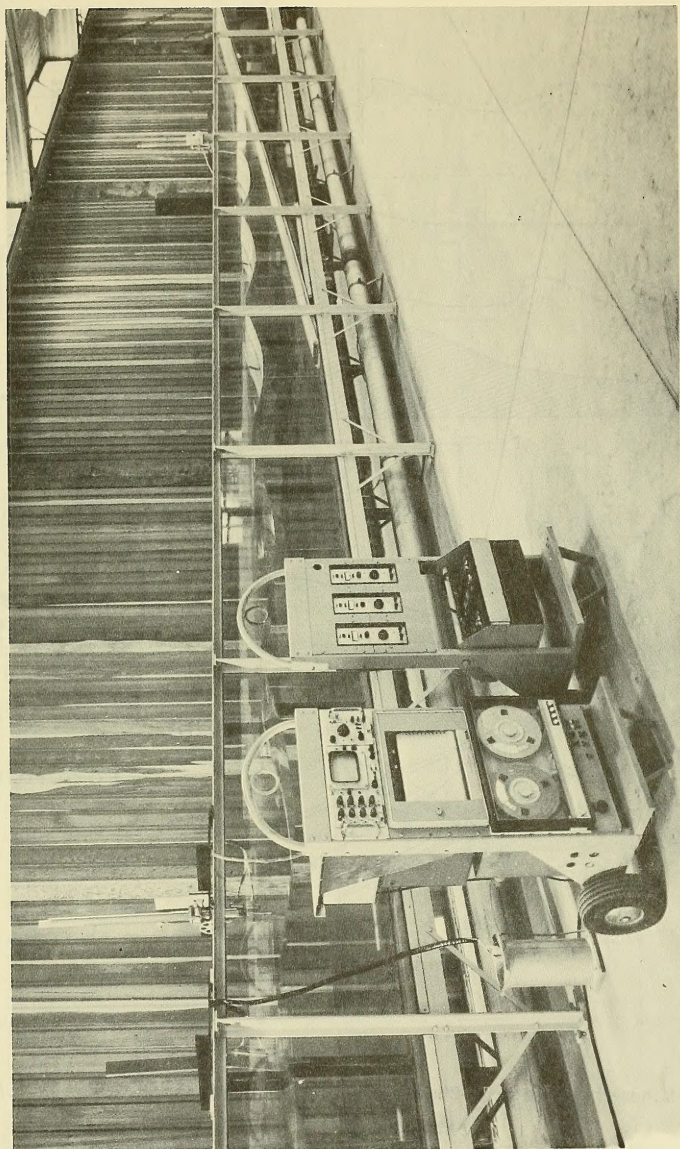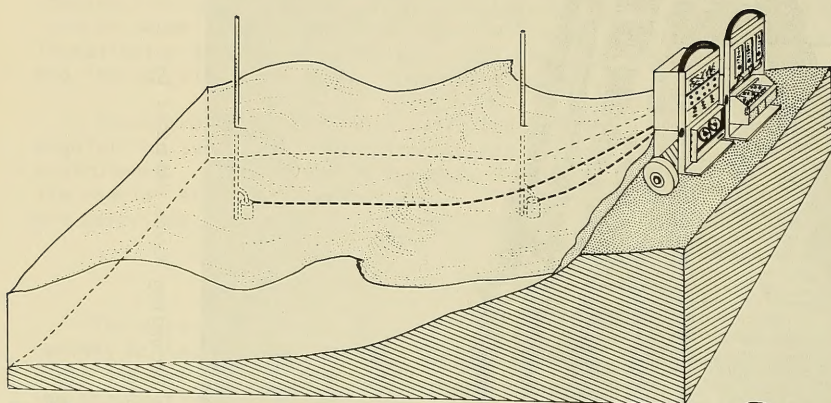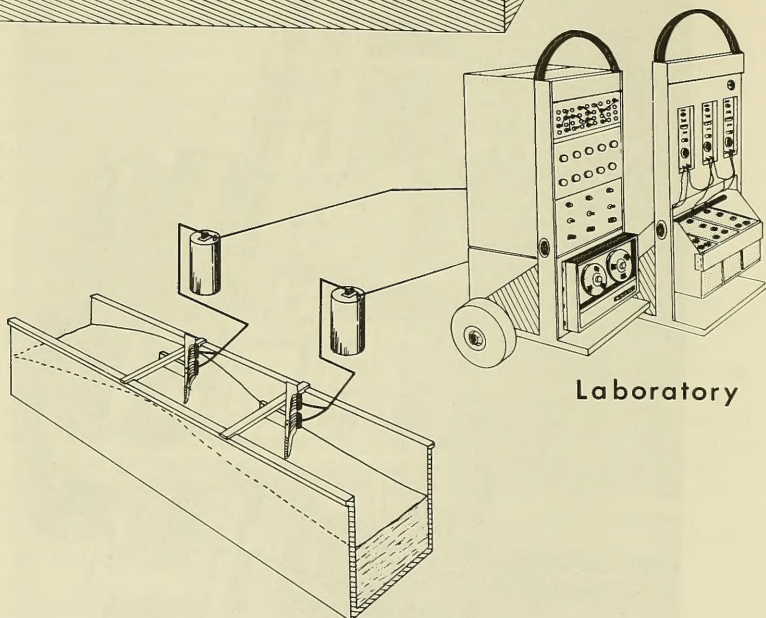*Notations refer to LITERATURE CITED on page 35.

Figure 1. Photograph of the Data Acquisition System Recording Waves Measured by the Mini-Digital Wave Staff (left background).

Field

Laboratory

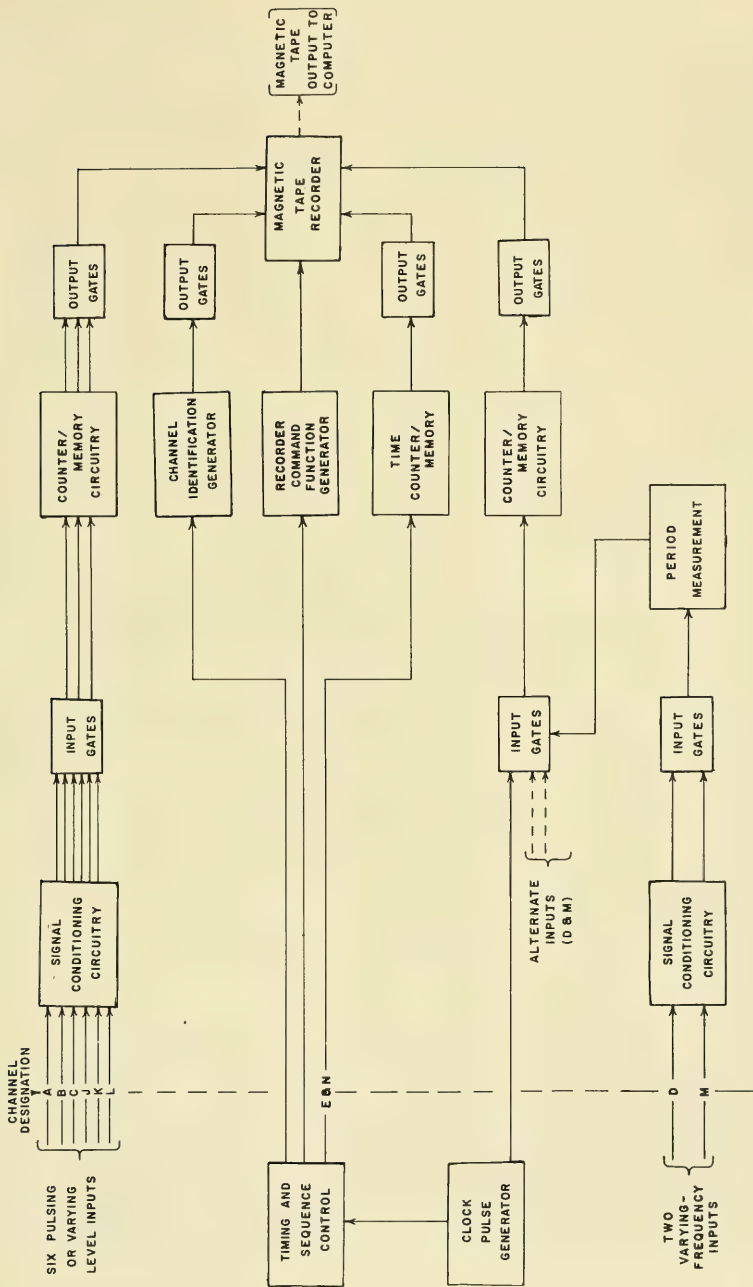Figure 2. Schematic Diagram Showing Field and Laboratory Uses of DAS.

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Figure 3. Block Diagram of the Data Acquisition System

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1. Channels and Gating Circuitry

Signal-conditioning circuits are included in the system and may be connected to receive signals from (1) instruments with a modulated-frequency output, (2) sensors with low-level outputs, such as strain gages, (3) variable resistance sensors and those with high-level outputs, and (4) instruments with outputs in pulse form, as from the digital wave staff. A block diagram of the data acquisition system is shown in Figure 3. Output signals from all sensors are converted to pulse form prior to being scanned by gating circuitry in the acquisition system. Therefore, the error voltage and cross-talk of an analog multiplexer are not introduced, since scanning of the input channels takes place in digital networks where voltage fluctuations do not present a problem. Using digital methods in the remainder of the processing system allows the input variable to be compared to a time reference, which can be held to greater accuracy than a voltage reference. The time base for this data acquisition system is introduced by a crystal-controlled clock pulse generator accurate to two parts in one hundred thousand. The signal from a modulated-frequency device, such as a Vibroton pressure sensor (United Control Corporation, Redmond, Washington) must be treated individually to obtain sufficient resolution. The data acquisition system has a period counter to measure frequency changes too small to detect with a simple cycle (line-crossing) counter.

The acquisition system in use at the Scripps Institution of Oceanography has a total of five counter/memory circuits to sample simultaneously one modulated-frequency input and three pulsing (digital) or three variable-level (d.c.) inputs. The fifth counter is used to maintain an accurate record of elapsed time. The total number of available input channels is doubled by time-sharing each counter with two input signals. The period counter may be used as a cycle counter; in which case, eight digital, or d.c., inputs may be recorded.

It should be noted that a single data counter could have been used if all inputs had been time-shared. However, there were several reasons for simultaneous sampling: (1) Phase comparison between data channels can be made without the inconvenience of repeatedly referring to the time channel for the relative time of sampling. (2) Each channel has its own counter, which is used to store information for a sufficient time to allow a simple integrating circuit to provide an analog read-out.

2. Power Supply

Power in the field for the acquisition system is usually obtained from automobile storage batteries. Current consumption for the logic circuitry is about 4 amperes. An additional 12 amperes is required for the d.c. to a.c. converter that powers the recorder. About eight 15-minute data runs may be made from a set of fully charged batteries without recharge. However, it is often convenient to maintain the charge on the batteries with a 20-ampere d.c. generator driven by a gasoline engine. This arrangement has been found to be more practical than to use a 60-cycle alternator which has the difficulty of keeping voltage and frequency constant.

3. Data Storage

The acquisition system counts in binary numbers, as do most digital counters, using the two characters, *"zero"* and *"one"*. These are represented electronically by the two states of a bistable component; on the magnetic tape they are represented by changes in the state of the magnetic coating. Seven locations, called "levels", are assigned across the width of the tape for the digits of the binary system. At any one location a binary *one* is represented by the presence of a magnetic pole; its absence indicates a *zero* (Hoagland and Bacon, 1960). In any level (sometimes called a "track") the locations are evenly spaced five thousandths of an inch between centers. Since each location contains information to define one "binary digit", it is said to contain one "bit". Note that a bit is the smallest particle of information handled by the electronic circuitry, yet ten bits can represent any data count from zero to over one thousand. This system handles 1200 bits per second, a rate limited primarily by the tape recorder.

Both magnetic tape and paper tape were considered for the storage of data. Magnetic tape was selected because the high recording rate required to sample many information channels eight times each second is not practical with paper tape. The arrangement of the information bits on the tape was designed to get the maximum density of information on the tape and to keep computer programming at a minimum (Figure 4). Information is transcribed into the seven levels (tracks) of each frame simultaneously. *Zeros* and *ones* are recorded in the seventh level as required by the computer for parity check. This format requires an odd number of *ones* to be in each frame. The seventh level is reserved by the computer for this parity procedure.

Because a tape record completely free of errors is virtually impossible to obtain in the field, the format permits the computer to search for and correct deviations from a specific arrangement of information on the tape. One method the computer uses to locate errors is to check that the number of *ones* in each frame is, in fact, odd. This "odd parity" check is used instead of "even" to eliminate the chance that all *zeros* may appear in one frame. A series of frames with all *zeros* is used by the computer to signify the end of a data record.

Each set of data frames is preceded by a frame which contains a binary-coded-decimal (BCD) alphabetic character to identify the data frames which follow it, indicating which signal channel is being recorded. The letters A, B, C, D, E, and J, K, L, M, N are used as identifiers for the ten channels because each of these characters is represented by a BCD code which includes a *one* in the sixth level. Figure 5 shows the coding for the ten letters. This data acquisition system uses the sixth level as a "flag" to enable the computer to sort the identification frames from the data frames. In Figure 4, the rectangular "boxes" indicate locations on the magnetic tape for individual binary bits of information. The solid black boxes indicate *ones*, and those with enclosed circles are *zeros*. Note that a *one* in the sixth level indicates to the computer the presence of an identification frame. A technique similar to this was introduced by Frank Snodgrass of the University of California, San Diego, in a punched paper tape system.
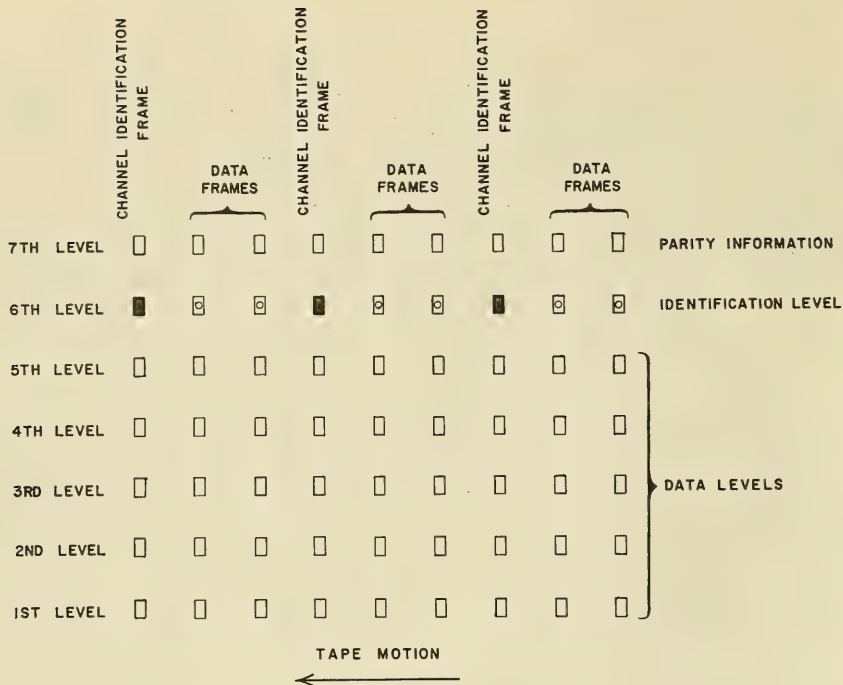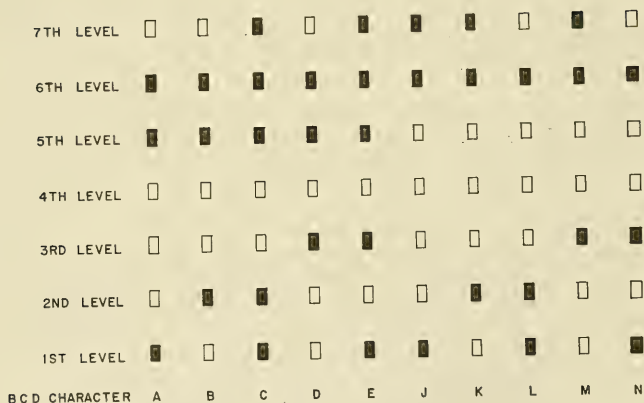
Figure 4. Magnetic Tape Format.

Figure 5. B C D Coding for Channel Identification.

A check for continuity and proper location of the identification frames is another method that the computer uses to locate errors. The first five levels of the frames between identification frames are used for actual data storage in straight binary form. There are five binary bits per frame with the five most significant bits recorded first and the five least significant bits recorded in the last frame of the data group. Those between, if any, are recorded in descending order of significance so that in each frame, the most significant bit is recorded in the fifth level and the least significant in the first level. This permits more numeric information per frame than does the BCD system which can record only one decimal digit in each frame.

It was decided to use two frames, or ten bits, for each data channel to give a measurement resolution of 0.1 percent per sample. Channels E and N, which are used to record elapsed time, have three frames each, enabling the binary time count to reach the equivalent decimal number of 2^{15} minus 1, or 32,767.

Section III. SPECIAL SENSORS

The data acquisition system is designed to accept a wide variety of sensor outputs. Several special sensors that have been designed or modified for use with DAS are described in the following paragraphs.

1. Digital Wave Staff and Mini-Digit Staff

The digital wave staff was designed to give accurate wave height and water level measurements in the surf zone (Figure 6). In principle, the staff operates by scanning in sequence a set of metallic contacts equally spaced on an electrical insulator. As each contact is scanned, an electrical pulse is transmitted over the signal line if the contact is under water. No pulse is sent if the contact is above water level. The result is a train of pulses, the number of pulses representing the height of the water on the staff (Figure 7). Attenuation or noise on the transmission line, within limits, will not affect the read-out, since the information is contained in the number of pulses present, not in their amplitude.

The operation of the scanning circuitry for the digital wave staff is illustrated in the logic diagram of Figure 8. The interrogator drives the input lines of the 16 x 8 matrix, applying a negative potential to each of the 16 lines in turn and keeping the remaining lines at a high impedance with respect to ground. Biasing circuitry maintains the high impedance lines at a slightly positive voltage, and the sequential scanning of the lines effects an alternating potential at each of the 128 external staff contacts. The alternating current minimizes electrolysis at the contacts.

Each of the output lines of the matrix is selected, in turn, by its line selector gate. The timing is arranged so that all eight output lines are scanned during the time interval in which one input line is interrogated

with a negative applied voltage. The matrix logic (Figure 9) is such that only once during a complete scanning sequence is any staff contact selected by the gating circuit while being subjected to a negative voltage from the interrogator. If the contact is above the water level, the negative voltage is sufficient to cause the solid state comparator to be held in a non-conducting condition and a binary zero (-0.4 volt) is indicated at its output terminal. If the negative voltage at the staff contact is reduced below a certain level due to the shorting effect of being immersed, the comparator output changes to a binary one and the terminal voltage changes to -5.8 volts. The point at which the change takes place is controlled manually by adjusting a threshold reference potential associated with the comparator. This manual control permits adjustment of the voltage response so that the staff may be made insensitive to salt spray and to water adhering to the staff above the measured level. The sensitivity may be increased when tap water is used in laboratory wave systems.

A pulse is generated in the output of the NAND gate only if a binary *one* is present at the output of the comparator during interrogation and selection of the staff contact associated with the particular pulse position in time. Thus, a train of pulses results when the contacts are scanned in sequence.

In actual use the wave staff is scanned at a rather high rate — usually sixty-four complete scans of the entire staff each second. The output pulses are maintained at constant width and amplitude, permitting a simple electronic integrating circuit to generate a continuous signal in analog form. This analog signal may be connected to a chart recorder for a visual field record of the wave height. The digital record is formed by selecting a sampling interval, connecting the pulse train to a binary counter for the duration of this interval, and recording the resulting count in binary code on magnetic tape. For digital recording, a timing oscillator within the electronics package is synchronized with the data acquisition system. When only analog recording is desired, the digital data acquisition system is not required. The timing oscillator is self-sustaining, permitting the staff output to be read directly on a standard, damped voltmeter or connected through an integrator to a chart recorder.

Some of the more important characteristics of the digital wave staff are:

    (1)   No calibration is required. The digital read-out is self-defining.

    (2)   The output signal may be transmitted over long distances in a simple three-conductor cable without loss of calibration.

    (3)   Calibration does not change with salinity of the water or adherence of saline water to the staff itself.

    (4)   Read-out, almost instantaneous, is limited only by the time required for electronic interrogation — not by mechanical inertia.

Figure 6. Photograph of Digital Wave Staff for Field Use. This staff has spacing of 2 cm between contacts. Note canister containing electronic logic circuitry.

A. Low Water Level

B. High Water Level.

Sampling Interval
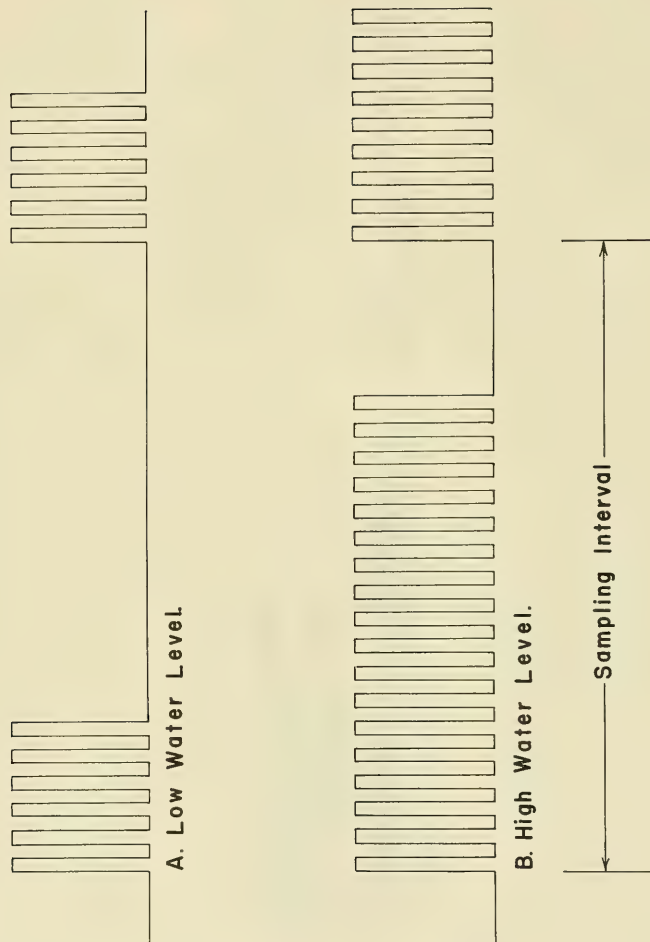
Figure 7. Schematic Diagram of Output Wave Forms for the Digital Wave Staff.

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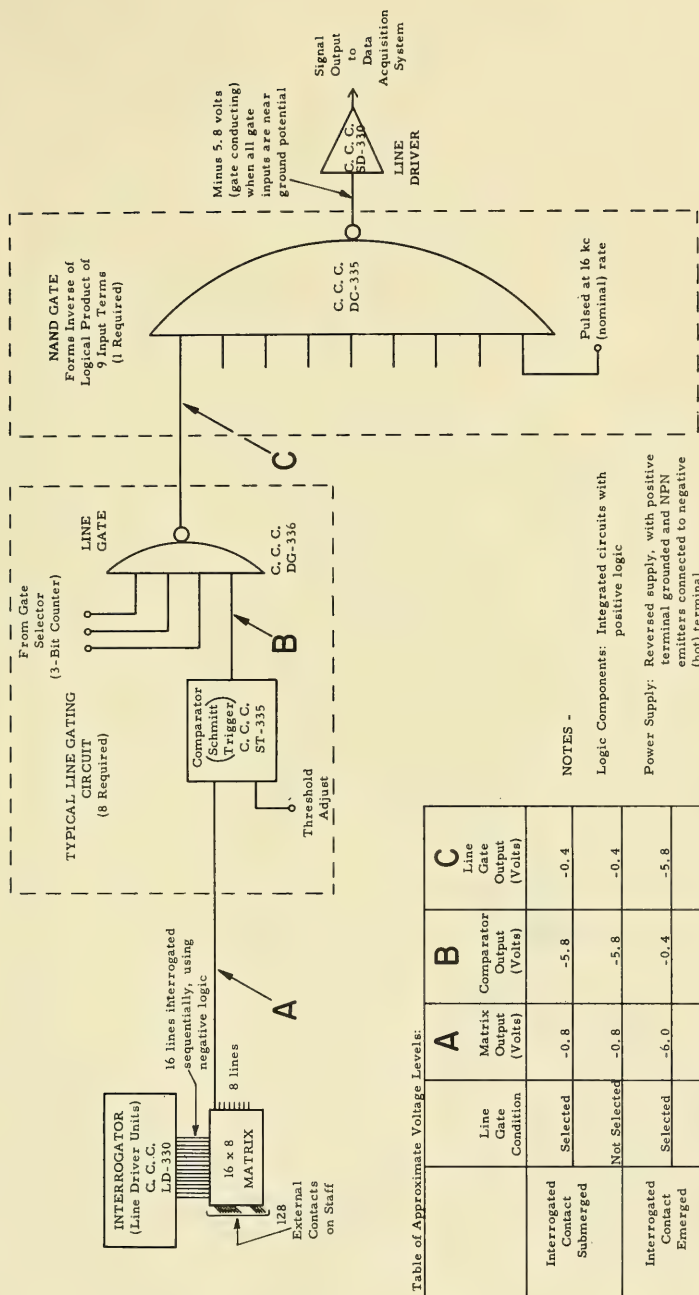
Figure 8. Logic Diagram of Electronics Package for Digital Wave Staff.

Table of Approximate Voltage Levels:

	Line Gate Condition	A Matrix Output (Volts)	B Comparator Output (Volts)	C Line Gate Output (Volts)
Interrogated Contact Submerged	Selected	-0.8	-5.8	-0.4
	Not Selected	-0.8	-5.8	-0.4
Interrogated Contact Emerged	Selected	-6.0	-0.4	-5.8
	Not Selected	-6.0	-0.4	-0.4

NOTES -

Logic Components: Integrated circuits with positive logic

Power Supply: Reversed supply, with positive terminal grounded and NPN emitters connected to negative (hot) terminal

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Figure 9. Diagram of 16 x 8 Logic Matrix for Digital Wave Staff Electronics Package.

8 LINES TO COMPARATORS

16 LINES FROM INTERROGATOR

detail

TO 128 EXTERNAL CONTACTS (SENSORS) ON STAFF

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As of this writing, digital wave staffs have been built in three different configurations. The first staff was built into a 10-foot length of 1¼-inch polyvinylchloride (PVC) tubing. It has 96 contacts placed at 3 cm intervals along the tube. Its self-contained logic circuitry for scanning the contacts is mounted on two printed circuit boards each 5 feet long and 1 inch wide. These are positioned inside the PVC tube and may be removed for repair if necessary.

A few staffs have been constructed from commercial fiberglass fishing rods. Each has 96 contacts placed at 2 cm intervals along the length of the rod. Separate brass cylinders house the logic cards that constitute the electronic circuitry. With these separate, universal electronics packages, the "plug-in" staffs may be constructed cheaply enough to be considered expendable.

Two "miniature" staffs with contact spacing of 2 millimeters have been built for use in recording small waves in the Hydraulics Laboratory. (See Figure 10). The miniature versions plug into the same electronics packages as the larger models. They are produced on double-sided glass-epoxy, printed circuit cards. Any number of staffs may be etched on cards from a photographic master made from a single drawing. The copper circuitry is gold plated to resist corrosion, and all but the contact edge is insulated with a polyurethane coating. Once a staff is designed and a photo master obtained, each miniature digital staff (called a "mini-digit") can be fabricated for a cost of about thirty dollars.

2. Vibrating-Wire Pressure Sensor

Inaccuracy of measurement results when the transmitted data is referenced to a voltage level as in the common strain gauge pressure transducer. Variations in the amplitude of a signal occur with induced noise on the transmission cabling, with temperature changes which may alter amplifier gain, and with changes in power supply voltage. On the other hand, when changes in a measured parameter are represented as corresponding changes in signal frequency, or in pulse pattern, the only troublesome conditions are those which may shift the phase of the signal.

A vibrating-wire type sensor is commonly used when very accurate measurements of the pressure field associated with waves are required (see Munk, Miller, Snodgrass, and Barber, 1963). Pressure variations change the tension on a wire which is driven at its natural frequency of vibration. A count of the resulting frequency in cycles per unit of time will give a read-out that lends itself well to digital recording. Special circuitry enables the vibrating-wire transducer to sense very small changes in pressure even in a very high pressure environment. This circuitry, as used in the acquisition system, is outlined in Figure 11.

A line-crossing detector, technically called a "Schmitt trigger" is used to generate a train of electrical pulses, each coinciding with a cycle from the output of the pressure sensor. An electronic gate is opened by a pulse from a reset pulse generator, allowing the signal pulses to be
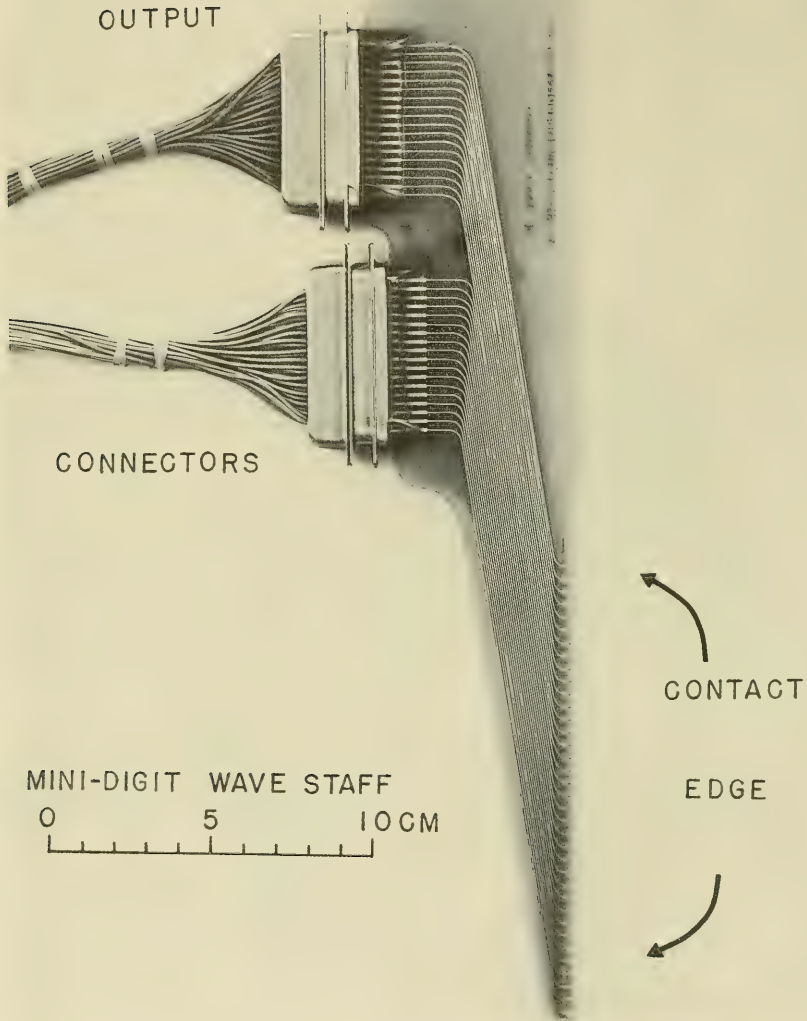
15

Figure 10. Photograph of Mini-Digital Wave Staff for Laboratory Use.
Contacts and connecting leads are printed on double-sided
printed circuit cards. There are 72 contacts on this staff,
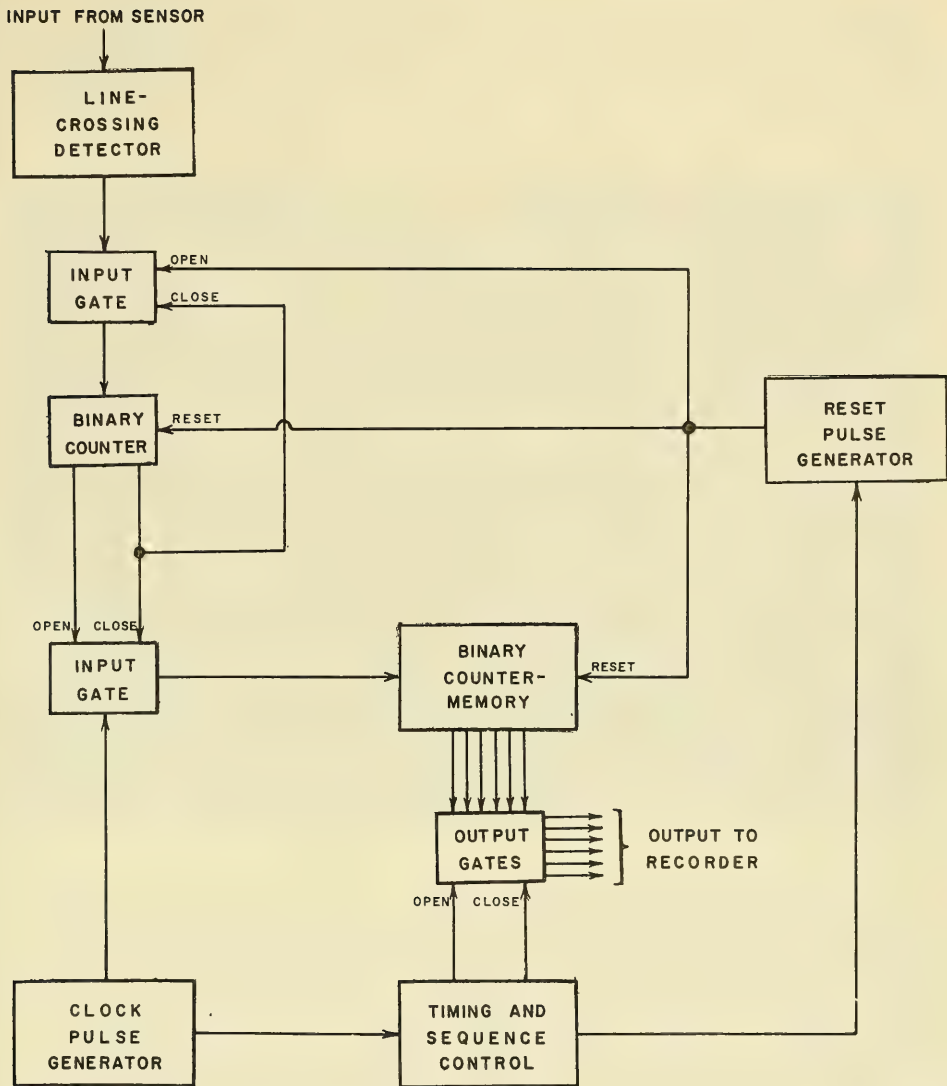half on each side. Spacing between contacts is 2 mm.

INPUT FROM SENSOR

Figure 11. Block Diagram of Period Counter for Use with Vibrating-Wire
Pressure Sensor.

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counted by a binary counter. At a predetermined count another gate is opened, allowing pulses from a two-megacycle-per-second clock pulse generator to be counted by a second binary counter. When the first binary counter reaches another predetermined count, both gates are closed and the flow of pulses to the counters is stopped. The time, in half-microseconds, is held as a binary coded number in the second counter and represents the period required for the predetermined number of pulses to flow into the first counter from the pressure sensor. The resolution of the pressure measurement is in direct proportion to the number and is limited only by the time allowed for sampling the sensor. When determined by the sequence control, gates connect the output of the counter to the tape recorder.

3. Savonius Current Meter

A current meter has been designed to utilize the digital logic basic to the data acquisition system. Its output is similar to that of the digital wave staff and has the same advantages listed in the discussion of the staff.

A miniature Savonius rotor was modified to produce 120 electrical pulses for each revolution. Sixty equally spaced holes near the periphery of one rotor end plate interrupt a light beam as the rotor turns. One pulse is generated as the beam passes through each hole, and another pulse is generated as the beam is interrupted.

The digital record of current flow is formed in the same manner as the record of wave height. A sampling interval is selected and a record is made of the number of pulses occurring during this interval. Since the pulses are electronically maintained at constant width, an integrating circuit may be used to form a continuous analog signal for a chart recorder is desired.

Several light sources were tested during the development of the current sensor. The final design incorporated a type L15-45 bulb manufactured by Pinlites, Inc. of Fairfield, New Jersey.

4. Synchronous Timing Lights

Accurate synchronization of observations, such as those from an underwater camera, with other measurements of the environment has been attained by providing a synchronous digital time display. Miniature indicator lamps provide a time code which appears in the field of the photograph and can be directly related to the wave and current data recorded by the data acquisition system. Synchronization is assured by driving the lamps with solid-state electronic switches operated directly from the binary time counter of the data acquisition system (DAS). The lights are arranged in groups of three for rapid visual read-out in an octal numbering system (Figure 12). A lamp is illuminated when a *one* is to be indicated in the binary bit it represents. The time code shown on the lights is printed out on the computer digital time series read-out and also on the direct analog chart read-out of DAS. An example of the

use of this synchronous system is given in Section IV following. The timing lights would function equally well for photographing wave phenomena through the glass walls of a laboratory channel.

Figure 12.   Underwater Photograph of Synchronous Timing Lights.   The octal count is 0131, which equals 89 decimal count.   Note the sand ripples at base of grid.   Grid dimensions are 10 cm (horizontal) by 5 cm (vertical).

The indicators themselves are No. 327 lamps.   They are rated to be powered from a 28-volt supply, but it was found that 18 volts applied to the lamps increases their life appreciably and provides sufficient illumination for underwater photography.   The block of twelve lamps is sealed

in a watertight housing with a thirteen conductor cable connecting it to DAS. Special connectors on the lamp housing allow the cable to be joined or removed while under water. Following is an explanation of how the lights are "read" in terms of octal numbers and then converted to decimal.

For a lamp display such as the synchronous timing lights (Figure 12), the octal count of any vertical column of three lights is given as:

	o	o	o	o	x	x	x	x
Column	o	o	x	x	o	o	x	x
	o	x	o	x	o	x	o	x
Octal count	0	1	2	3	4	5	6	7

where "x" indicates a lighted lamp and "o" indicates an unlighted lamp.

Each column represents an octal digit. The equivalent decimal count of each octal digit is found by multiplying the octal count by the appropriate factor. The total decimal count is the sum of the individual decimal counts for all columns, as shown below:

SYNCHRONOUS TIMING LIGHTS (display of 12 bits)	o o o o o o x o o x x x			
Octal count	0	1	3	1
Factor	8^3	8^2	8^1	8^0

Total decimal count = $0 \times 512 + 1 \times 64 + 3 \times 8 + 1 \times 1 = 89$.

Section IV. PROGRAMMING TIME SERIES

A "program" is a list of instructions that enables the computer to read and manipulate input data and to write or print-out the processed data. The programming of time series* to obtain wave spectra and cross-spectra utilizes the harmonic analysis by digital methods developed by Tukey (Blackman and Tukey, 1959) (Munk, Snodgrass and Tucker, 1959). This method is the basis for the development of a versatile computer program, BOMM, which facilitates the manipulation of large numbers of synoptic time series. The following incomplete treatment of wave analysis by digital manipulation is intended only as an outline to aid in interpreting the programmed results from the data acquisition system. The original references should be consulted for a more detailed treatment of the subject.

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*Since the writing of this manuscript much interest has developed around a more efficient method for performing a Fourier transformation with a digital computer. (See Appendix A.)

1. One-Dimensional Power Spectra

The concepts leading to simple wave spectra can be illustrated by assuming that a train of pure sine waves is propagated over the water surface such that the water surface elevation η varies with distance x and time t:

$$\eta = \tfrac{1}{2}H \cos (kx - \sigma t) \tag{1}$$

where $k = 2\pi/L$ is the wave number, $\sigma = 2\pi/T$ is the wave frequency, and H, L, and T are the wave height, length, and period, respectively. The mean-square elevation of the water surface $\langle \eta^2 \rangle$ at any time is given by:

$$\langle \eta^2 \rangle = \frac{1}{L} \int_0^L \frac{H^2}{4} \cos^2 (kx - \sigma t) \, dx \tag{2}$$

since:

$$\int_0^{} \cos^2(\cdots) = \frac{1}{2}x + \frac{1}{4k}\sin(2kx)\Big|_0^L$$

holding σt constant, this becomes $\langle \eta^2 \rangle = H^2/8$. The mean energy (including both kinetic and potential) per unit area of water surface is equal to the product of the mean-square elevation and the weight per unit volume ρg of the fluid, then

$$E = \rho g \langle \eta^2 \rangle = \frac{1}{8} \rho g H^2 \tag{3}$$

Since ρg is nearly constant for sea water, it is customary to use the mean-square elevation $\langle \eta^2 \rangle$ as a measure of wave energy.

If the sine wave is amplitude-modulated in a random manner, the wave train can no longer be represented by a single height, but includes a range of heights. In this case, the appropriate wave height statistic in equation (3) becomes the root-mean-square wave height H_{rms} (Longuet-Higgins, 1952). The significant wave height, $H_{1/3}$, is related to the rms wave height of simple narrow band spectra by the relation

$$\tfrac{1}{2}H_{1/3}^2 = H_{rms}^2 = 8 \langle \eta^2 \rangle \tag{4}$$

It should be noted that the root-mean-square amplitude becomes $a_{rms} = \sqrt{2} \cdot$ [root-mean-square elevation] $= \sqrt{2} \cdot \eta_{rms}$.

a. Real Waves. Real ocean waves vary in both frequency and amplitude in a far more complex manner than the simplified waves illustrated above, and their spectral analysis requires a more sophisticated technique. Also, the presence of higher harmonics associated with the asymmetry of waves in shallow water further complicates interpretation in terms of simple waves.

The computation techniques developed in communication engineering (Blackman and Tukey, 1959) for determining the spectra of signals in the presence of noise have been found to be applicable to the analysis of ocean waves (Munk, Snodgrass and Tucker, 1959). The general procedure is to obtain a digital time series of wave elevation, $\eta(t)$, or a related parameter such as pressure, spaced at equal sampling intervals Δt. The data is then processed by a digital computer. After checking for errors and correcting

for tides and depth by proper mathematical filters, the autocovariance is then computed.

The autocovariance or autocorrelation C_{11} (τ) is defined as

$$C_{11}(\tau) = \left\langle \eta_1(t) \cdot \eta_1(t - \tau) \right\rangle \tag{5}$$

Here τ is a lag interval having values $k \cdot \Delta t$ where k is a positive integer and $\eta_1(t)$ is the time history of water level fluctuations, assumed statistically stationary and oscillating about zero as a mean value. $\left\langle \ \right\rangle$ designates an average taken over all values $\eta_1(t)$. The subscript eleven (as C_{11}) is introduced here to prevent ambiguity with the cross-correlation between two time series introduced in the following sections.

The spectrum $S_1(\sigma)$ is then defined as the cosine transform of the autocovariance

$$S_1(\sigma) = \frac{2}{\pi} \int_0^\infty C_{11}(\tau) \cdot \cos(\sigma\tau) \cdot d\tau \tag{6}$$

This is usually plotted against frequency $f = \sigma/2\pi$ giving

$$S_1(f) = 4 \int_0^\infty C_{11}(\tau) \cdot \cos(2\pi f\tau) \cdot d\tau \tag{7}$$

Now $C_{11}(\tau)$ has units of $(length)^2$ and $d\tau$ has units of time. $S_1(f)$ is thus a measure of the energy per unit frequency and is sometimes referred to as the estimate of the energy density.

Since the autocovariance and the spectrum are Fourier transforms of each other, the spectrum can be expressed in more compact notation using two-sided forms ($-\infty$ to $+\infty$) with exponential kernels (see Cox, 1962, p. 755). However, because the autocovariance function is symmetrical, the same results are obtained from twice the value of the one-sided cosine transform. One-sided forms are used in this and following developments because they follow more closely the actual manipulations performed by the digital computer.

  b. Error and Aliasing. The spectral analysis yields estimates of the mean energy attributable to sinusoidal wave components in contiguous elemental frequency bands of width Δf. The width of the band is determined by the data sampling interval Δt and the number of chosen lags m by the relation

$$\Delta f = \frac{1}{2\Delta t m}$$

The estimates of energy density are usually given in units of the mean-square elevation $\left\langle \eta^2 \right\rangle$ per Δf. The estimates are subject to errors, whose probability distribution is Gaussian (normal). The confidence
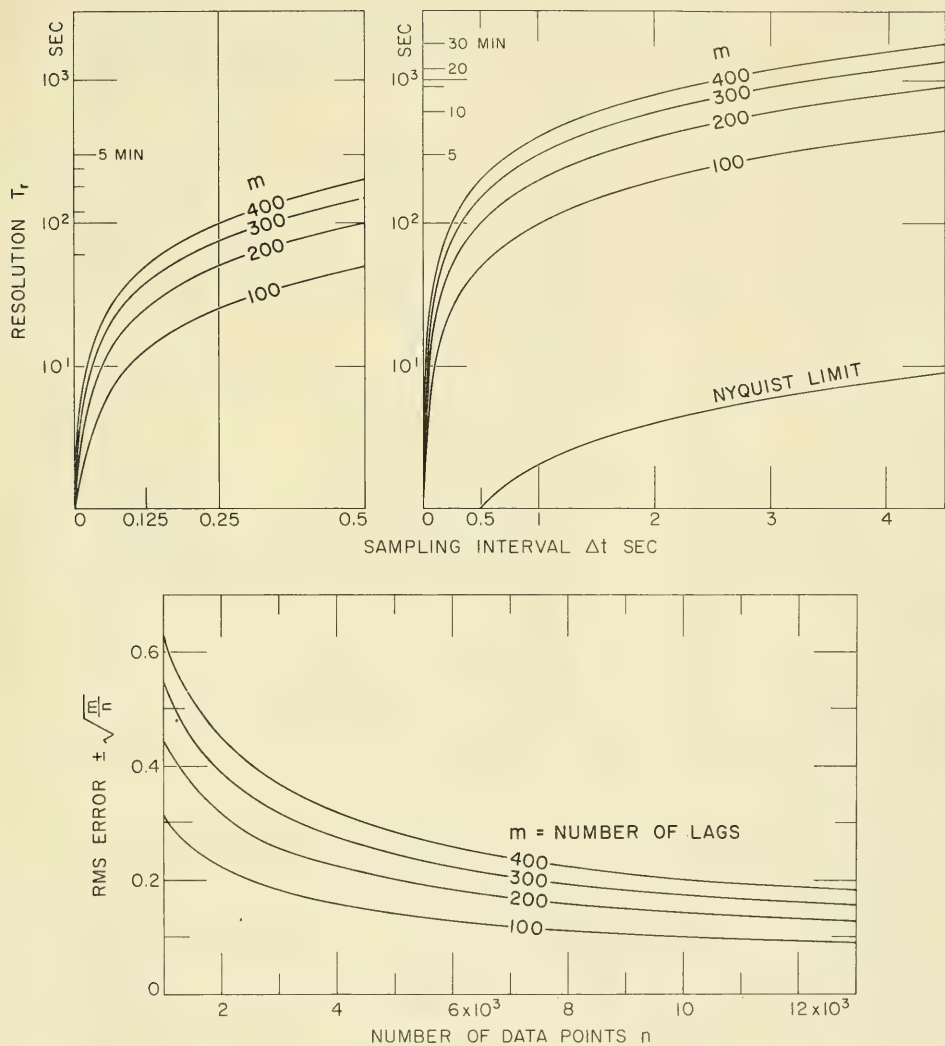
Figure 13. Resolution (T_r) and RMS error ($\sqrt{m/n}$) as Functions of the Sampling Interval Δt, the Number of Data Points (n) and the Number of Lags (m).

limits of an estimate are a function of the degrees of freedom $\gamma = 2 n/m$, where $n = T_+/\Delta t$ is the number of data points, T_+ is the total record length, and m, the number of lags. The root-mean-square error of the estimate, for 95 percent confidence limits, is found to be $\sqrt{2/\gamma} = \sqrt{m/n}$. This can be interpreted as the probability that 95 percent of the samples will fall with $\pm\sqrt{m/n}$ of the estimate. Graphs illustrating the effects of record length (total number of samples) and sampling interval on the expected error are shown in Figure 13.

The frequency range of the spectrum obtained from digital computation techniques is limited in both directions. No real information is obtained for frequencies lower than the resolution frequency $f_r = 1/T_r = 1/\Delta tm$, where m is the total number of lags and T_r is the maximum lag in real time between comparisons of two time series. Also oscillations having frequencies greater than the Nyquist (or folding) frequency, $f_n = 1/2\Delta t$. will give aliased or ghost signatures that may appear in the frequency interval 0 to f_n (Blackman and Tukey, 1959, p. 31).

The discrete sampling at equally spaced intervals Δt produces sum and difference frequencies

$$f_a = (k/\Delta t) \pm f_1 = 2 kf_n \pm f_1 \tag{8}$$

where f_1 is the frequency of a real oscillation and k is an integer. If f_1 is less than f_n, both sum and difference frequencies f_a fall outside of the frequency interval 0 to f_n. However, oscillations with frequencies greater than f_n will have aliased frequencies f_a that fall within the interval 0 to f_n. These aliased or ghost frequencies will be indistinguishable from real oscillations of the same frequency.

To prevent the occurrence at the sensor of energy in the frequency range above f_n, it is customary in wave pressure measurements to place the pressure sensor at sufficient depth to filter out high frequency "noise". For wave staffs and other water level sensors, it is necessary to decrease the sampling interval Δt until energy in frequencies above $1/2 \Delta t$ is decreased to acceptable levels.

The above considerations are illustrated by two spectra of waves measured in a laboratory channel (Figure 14). The spectra are computed from synoptic measurements using two mini-digit wave staffs as sensors. One sensor (Staff B) was placed in the constant depth portion of the channel (still water depth 50 cm) and the other sensor (Staff C) at the point where the waves broke after shoaling over an impermeable 1:12 slope. The wave maker generated simple harmonic motion of 0.88 cps; and the wave heights, as measured by pointer gages, were found to be 100 mm at the constant depth portion of the channel and 120 mm at the breaker point. The wave staffs were sampled 8 times per second for 15 minutes, giving 7,200 data points for each channel. The data was analyzed using 200 lags which gives a root-mean-square error of ±0.176 of the estimate of energy density. The energy density for the wave spectra is expressed in $mm^2/\Delta f$,
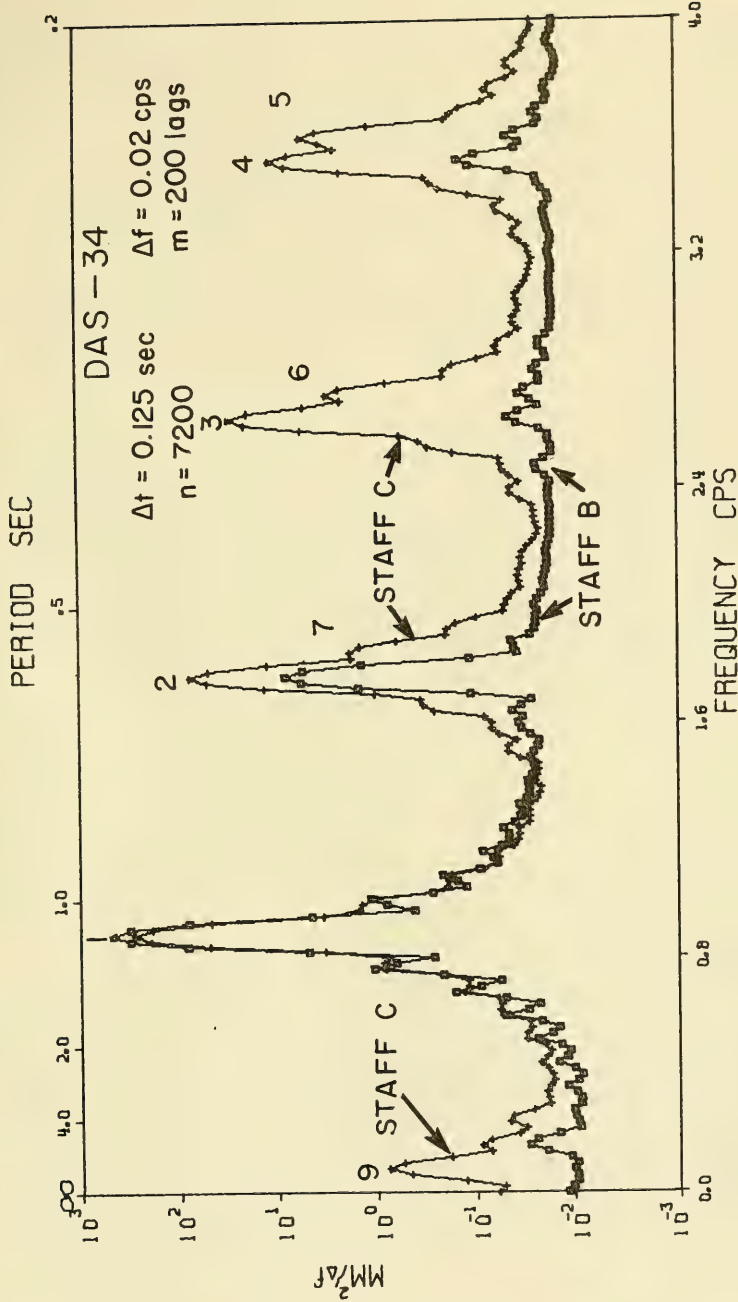
Figure 14. Spectra of Waves Measured Simultaneously in the Laboratory Using Mini-Digit Wave Staffs as Sensors. Staff B was in the constant depth portion of the wave channel (stillwater depth 50 cm) and Staff C at the breaker point after waves shoaled over 1:12 slope. Wave maker generated simple harmonic motion of 0.88 cps. Spectral peaks are identified by numbers giving the order of the harmonic where 1 is the first order or fundamental, 2 the second order or first harmonic, etc. Orders higher than 4 appear as aliased frequencies.

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where Δf is 0.02 cps. With the above values the resolution frequency f_r and the Nyquist frequency f_n become 0.04 and 4.0 cps, respectively.

It is apparent from Figure 14 that both spectra have significant harmonics, but that the most prominent harmonics are associated with the spectrum of the breaking wave because it has the least sinusoidal shape. The spectral peaks are identified by numbers giving the order of the harmonic, where one is the first order or fundamental, two, the second order or first harmonic, etc. For this analysis, with a Nyquist frequency of 4.0 cps, it is clear that any harmonic above order four will have a frequency greater than the Nyquist. Thus the fifth order harmonic, with a frequency of 4.4 cps, folds over and appears as a ghost signature with a frequency of $f_a = 8.0 - 4.4 = 3.6$ cps. For these breaking waves there is identifiable energy folded over for harmonics as high as the ninth order.

2. Two-Dimensional Power Spectra

The spectrum of a single time series as given by equations (6) and (7) is one-dimensional and applies to the situation where a single staff is essentially a "blind" sensor. If synoptic time series are obtained at two or more points in space and there is coherence between points, then the data may be interpreted as having other dimensions commensurate with the geometry of the sensor array. The analysis requires the computation of the autocovariance and spectra of each series (equations (5) and (6)) as well as the cross-correlation (two-dimensional covariance) between time series, and their cosine and quadrature spectra.

The two cross correlations between time series $n_1(t)$ and $n_2(t)$ can be defined as

$$C_{12}(\tau) = \left\langle n_1(t) \cdot n_2(t - \tau) \right\rangle \tag{9}$$

and

$$C_{21}(\tau) = \left\langle n_2(t) \cdot n_1(t - \tau) \right\rangle \tag{10}$$

where τ, n, and t are defined in equation (5) and the subscripts 1 and 2 refer to time series 1 and 2.

The cosine spectra and quadrature spectra for these two time series become

$$P_{12}(f) = \int_0^\infty [C_{12}(\tau) + C_{21}(\tau)] \cdot \cos(2\pi f \tau) \cdot d\tau \tag{11}$$

and

$$Q_{12}(f) = \int_0^\infty [C_{12}(\tau) - C_{21}(\tau)] \cdot \sin(2\pi f \tau) \cdot d\tau \tag{12}$$

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With these definitions the coherence $R_{12}(f)$ and the phase difference $\phi_{12}(f)$ between time series 1 and 2 become:

$$[R_{12}(f)]^2 = \frac{[P_{12}(f)]^2 + [Q_{12}(f)]^2}{S_1(f) \cdot S_2(f)} \qquad (13)$$

and

$$\tan [\phi_{12}(f)] = \frac{Q_{12}(f)}{P_{12}(f)} \qquad (14)$$

where S_1 and S_2 are the power spectra of time series 1 and 2, respectively, as defined by equation (6), and where positive values of ϕ_{12} represent a phase lead of series 2 relative to series 1.

The coherency and phase difference between the records from two stations can be interpreted as follows: If any two time series (1, 2) are "played" through a narrow filter peaked at some frequency f, and the filtered 1 series lagged relative to the filtered 2 series by a variable phase ϕ, the plotted angle is that value of ϕ for which the correlation is a maximum; and the plotted coherence R is the value of this maximum correlation. It should be noted that the phase relation between records is meaningful only where there is good coherency between records.

The spectra and the coherence and phase between two digital wave staffs mounted near the surf zone are shown in Figure 15. Note that for frequencies near the major spectral peaks, there is good coherence between staffs and that the phase shift is uniformly progressive for changing frequency. The phase shift between staffs gives a measure of the direction of energy flux associated with the passage of these waves.

3. Adaption to BOMM Program

Standard punch cards have proven to be most useful for instructing the computer in processing the data. Once a program is established, it may be used as often as desired. Minor changes to the program are easily accomplished by removing or adding cards to the "deck".

A preliminary computer program has been written for the output of the data acquisition system (DAS) to facilitate its further programming by BOMM. The preliminary program has two purposes: (1) to add "record gaps" to the tape record and (2) to convert the information in the data frames from a binary to a binary-coded-decimal (BCD) system. Record gaps are necessary to provide places for the computer tape-reading equipment to pause while the information in each record is electronically registered in proper memory banks within the computer. Record gaps are not generated by the DAS because this would permit data to be lost during the time the gap is put on the tape. The conversion to BCD is required by the BOMM program to enable it to locate errors in the record. DAS writes data in straight binary form to reduce the amount of logic equipment and the length of magnetic tape needed to record a given amount of data.
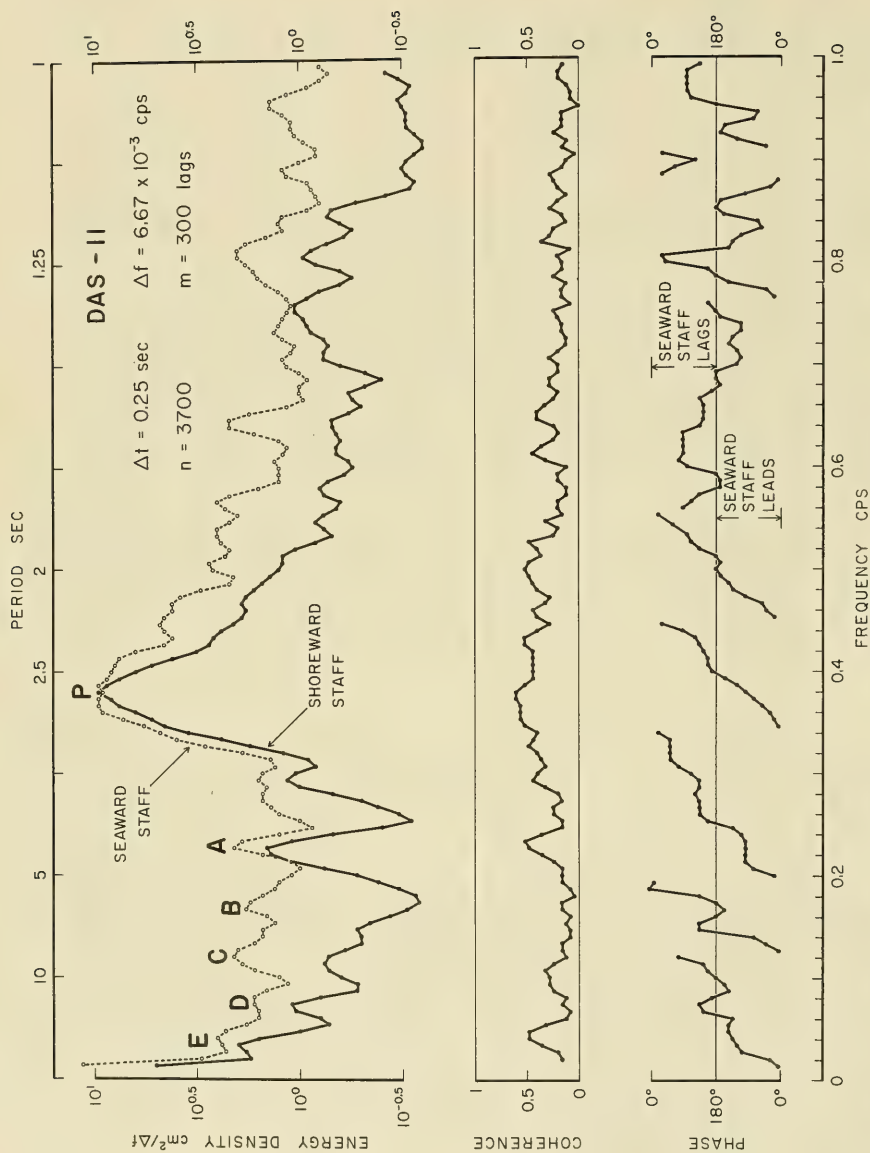
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Figure 15. Wave Spectra and Cross-Spectral Analysis for Two Members of an Array of Digital Wave Staffs, El Moreno, Gulf of California, Mexico. Shoreward staff was in the surf zone, and seaward staff outside of the breaker zone. Breaking waves were approximately 60 cm high.

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In practice, the preliminary program is used to read the information from a small tape reel used in the field and, after making the necessary changes, to record the data on a large tape reel for more permanent storage. The smaller reel of tape may then be reused in the field, and several data "runs" may be stored on the large reel. An indexing system permits immediate location of any data run.

The BOMM program in use at Scripps is stored on magnetic tape, but it could also be stored on cards. Several tape reels are used by BOMM; and these, along with the data input tape generated by the preliminary program, must be mounted on the computer tape-handling equipment prior to starting the data processing. The contents of the control card deck are transferred to a system input tape which defines the operations to be performed by the computer.

The following instructions must appear as statements on the control cards for calculating power spectra from measured data:

(1) Identification of the job for administrative purposes.

(2) Identification of the tapes on the tape-handling equipment.

(3) Code transformations, if needed.

(4) Instructions for reading the data, including a description of the format used.

(5) Instructions for correcting gross errors.

(6) Instructions for printing statistical parameters and distribution functions for the data channels, if desired. The computer processing may be halted here for a visual inspection of data statistics before continuing with the power spectra calculations.

(7) Designation of the correlation procedure. Two autocorrelations and two cross-correlations are formed from each pair of data time series (equations (5), (9) and (10)). Each correlation creates a series with a length determined by the number of lags.

(8) Designation of mathematical filtering to be used. Since the correlation series are of finite length, they must be modified by a "lag window" which acts as a filter to minimize side lobes in the power spectra plots. The filter characteristics must be chosen to concentrate real measured energy into its main lobes while attenuating the side lobes as much as possible. A practical compromise in filter transfer characteristics has been reached by using a Parzen curve with full transmission at zero frequency and zero transmission at the Nyquist frequency. This type of filtering was used to produce the plots of Figures 14 and 15 on pages 25 and 28.

(9) Instructions for formation of power spectra from cosine transforms
     of auto-correlated terms (equation (7)).

(10) Instructions for formation of co- and quad-spectra from cosine
      transforms of sums and differences of cross-correlated terms
      (equations (11) and (12)).

(11) Instructions for writing the processed series on a system output
      tape in a form suitable for plotting curves of the required
      functions.

The information on the output tape may be used at any time to plot
rough graphs on a printer, or for drawing smooth curves on an X-Y plotter.
Figure 14 is a reproduction of several curves drawn by a plotter.

Section V EXAMPLES OF FIELD AND LABORATORY INSTRUMENTATION

The multi-channel input feature of the data acquisition system permits
several sensors to be arranged as needed and then sampled simultaneously
resulting in a multi-dimensional data pattern. The sensor arrangements
described here have been employed in the study of nearshore phenomena.

1. Array of Digital Wave Staffs for Longshore Component of Wave Power

The simultaneous recording of one or more arrays of wave staffs is
necessary if the directional properties of waves are to be measured. A sche-
matic arrangement of two arrays of four digital wave staffs and a vibrating-
wire pressure sensor is shown in Figure 16. The plan here is to economize
the number of required wave staffs by employing the optimum irregular spacing
sequence and to obtain measurements in and outside of the surf zone from a
single installation during the low and high stands of the tide.

A very simple one-dimensional array of four staffs with spacings of 1,
3, and 2 units will give correlations of the regular array (uniformly spaced)
of 1, 2, 3, 4, 5 and 6 units (Barber, 1962). For maximum efficiency one
unit of spacing should be approximately one-quarter wave length. The use
of two arrays of four each, as illustrated in Figure 16 should provide good
measures of the direction of incident energy flux associated with incoming
waves, as well as an assessment of the modes of trapped energy in the form
of edge waves, or other waves such as surf beat and seiche.

Successful field measurements from two sensors of a simple array have
been obtained and are shown in Figure 15 on page 28. Comparison of the power
spectra for the two digital wave staffs shows that the sea-breeze waves and
the breaking waves both have power spectra peaked at 2.63 sec. (frequency
0.380 cps) and that the spectrum for the seaward staff has a somewhat broader
peak. Also, the general background noise is greater at all frequencies for
the seaward staff. A series of minor spectral peaks, with frequencies less
than that of the principal peak, occurs in both spectra. These minor spectral
peaks, with only one exception, occur at approximately the same frequency in
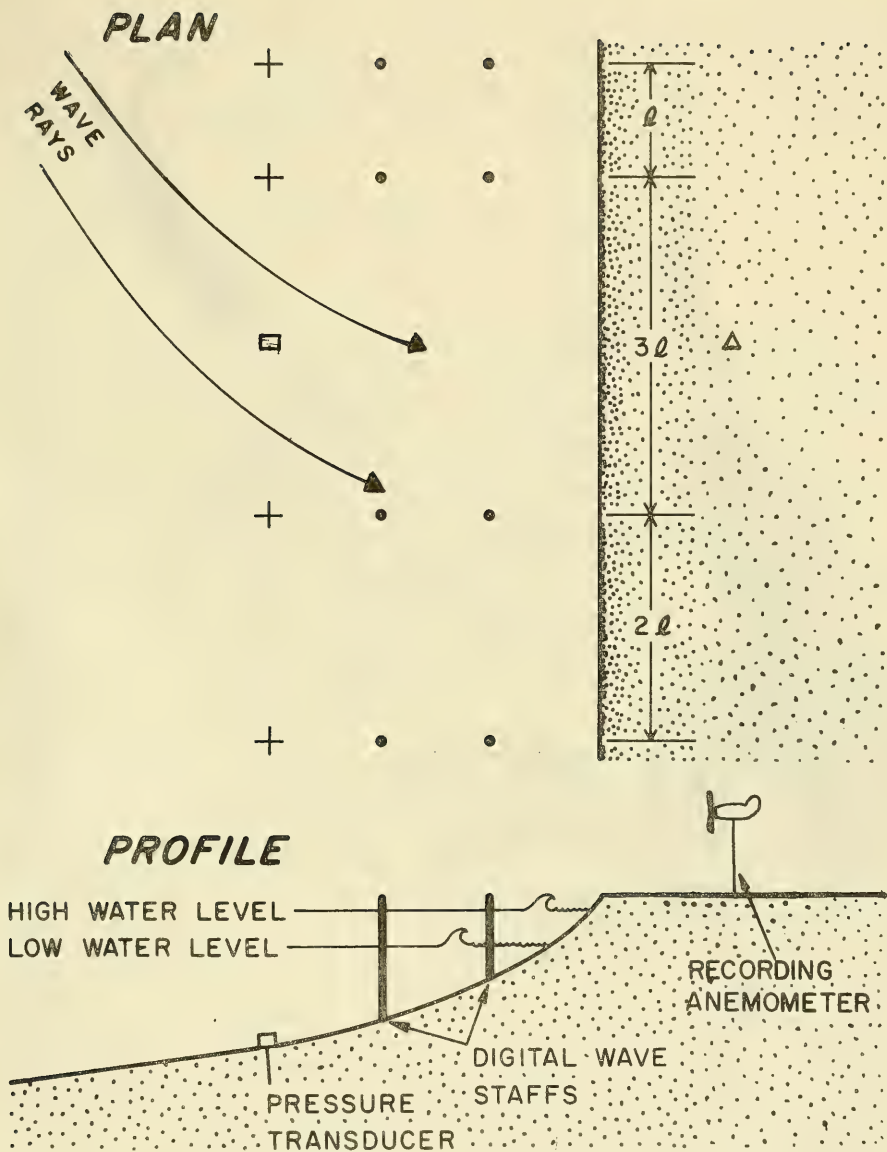both analyses. They do not appear to result from aliasing or side band beat

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Figure 16. Schematic Diagram of Array for Measuring Nearshore Wave Modes. Cross-spectral analysis shown in Figure 15 is from an offshore-onshore pair of such an array.
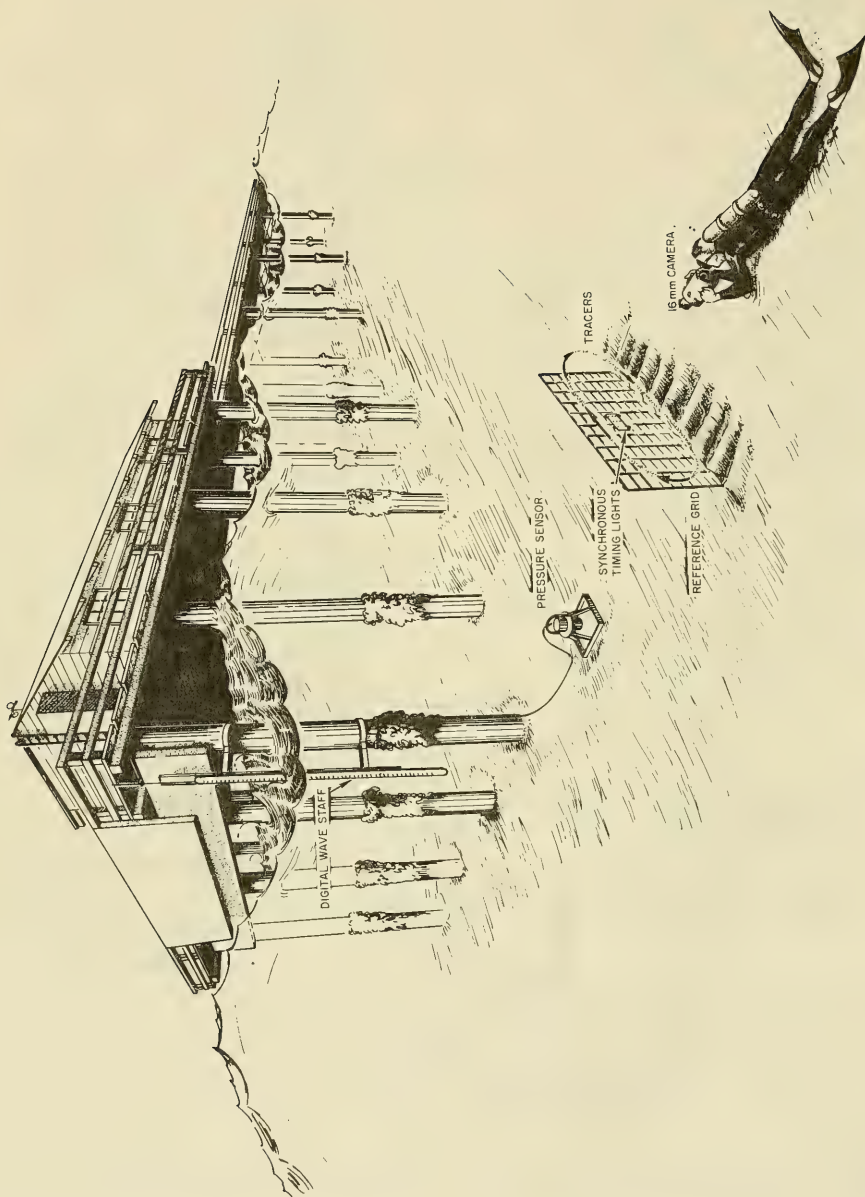
Figure 17. Schematic Diagram of Instrument Layout for Investigating the Mechanics of Sand Transport. An underwater photograph of the synchronous timing lights and reference grid is shown in Figure 12, and the data plots from a series of motion picture frames are given in Figure 18.

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(Blackman and Tukey, 1958, p. 70), and the confidence limits for the analysis suggest that they are real. The minor peak, labeled E, with period of about 25 to 30 seconds, also coincided (a) with the observed periodicity in the groupings of high and low waves in the surf zone, as measured from the analog record of the waves, and (b) with the pulsation period of rip current intensity.

The same array geometry as Figure 16, using mini-digital staffs, should provide useful information in model wave basins.

2. Mechanics of Sand Transport by Waves and Currents

Some preliminary results have been determined from an underwater photographic study of the motion of sand grains near the bottom. The arrangement of instruments is shown in Figure 17 and includes: synchronous timing lights mounted on a rectangular grid, digital wave staff for surface wave heights, and vibrating-wire transducer for wave pressure at the bottom.

The photographic analysis of sand motion near the bottom and wave-induced oscillatory currents is keyed directly to the data acquisition system by means of the synchronous timing lights. The trajectory of water particles near the sand bed is determined by photographing the motion of neutrally buoyant particles against a reference grid as shown in Figure 12. The height of the sand suspension is estimated directly from the photographs, pending incorporation of a sensor for concentration of suspended material.

Figure 18 illustrates the analysis of a typical photographic sequence. The surface wave profile is plotted (top) by the computer from data provided by the digital wave staff with the pressure sensor as a backup tool. That portion of the plot from 180 to 191 seconds has been analyzed photographically, and the horizontal component of the orbital water velocity is presented (center) and related in time to the height of the suspended sediment above the sea floor (bottom). This particular sequence shows a maximum sediment suspension during the time of maximum acceleration and deceleration, rather than during the time of maximum orbital velocity. Suspension of sediment during this phase of the orbit appears common for conditions where the orbital velocity does not exceed about 50 cm/sec. At higher orbital velocities, the sand is observed to more as a sheet flow within the layer of near bottom shear dispersion, with maximum suspension during maximum orbital velocity.
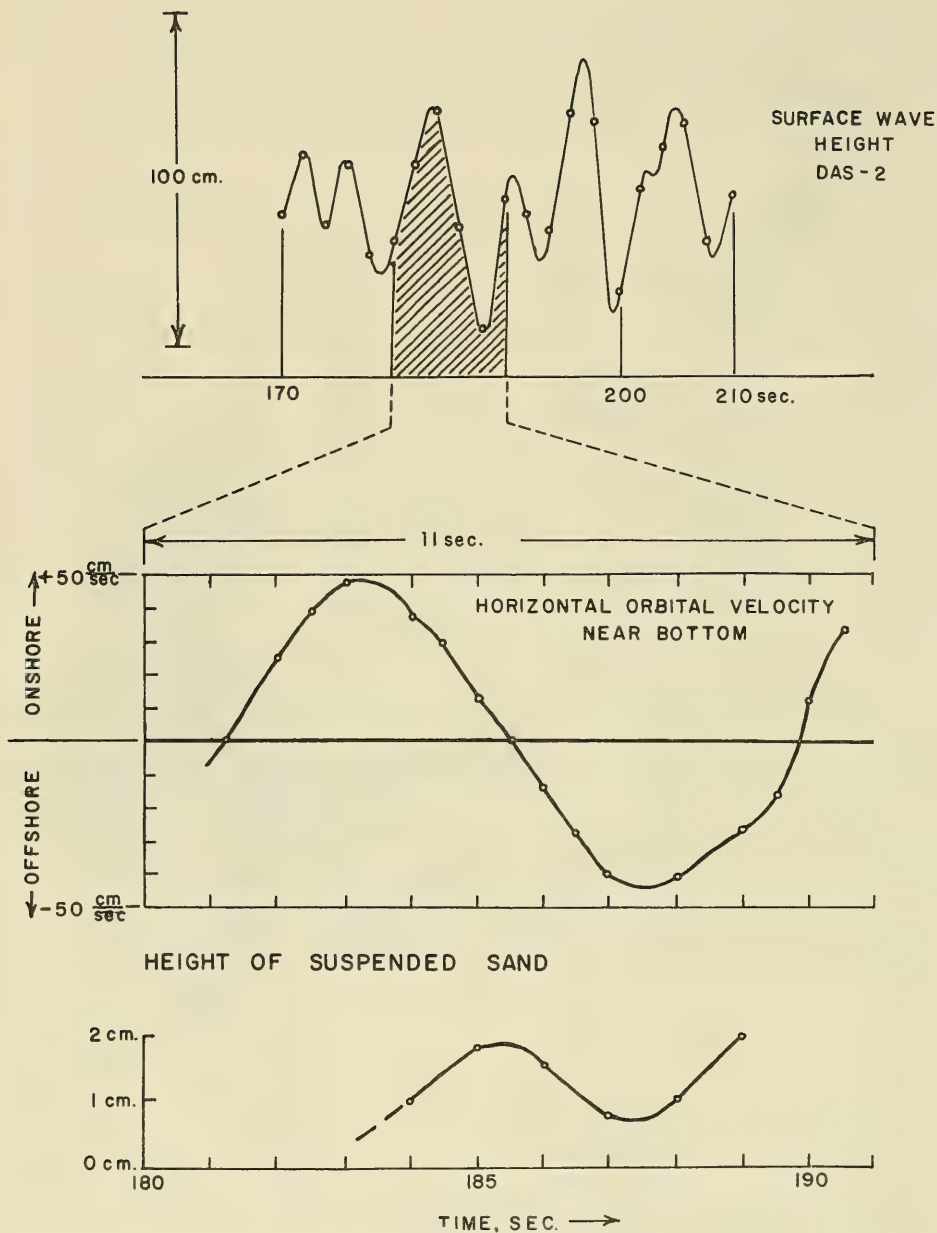
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Figure 18. Orbital Motion and Sand Suspension Measured off the Scripps Institution Pier Employing the Instrument Layout Shown in Figure 17. Surface wave height measured by digital wave staff and obtained from the magnetic tape read-out. The orbital velocity and heights of suspended sand were obtained from underwater motion pictures synchronized as shown in Figure 12.

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RECENT TRENDS IN COMPUTER PROGRAMMING FOR SPECTRAL ANALYSIS

An appreciable savings in computation time can be achieved by using
an arithmetic algorithm developed by Yates (1937) and expounded later for
use in Fourier analysis (Good, 1958). The algorithm was modified recently
to adapt it to the binary arithmetic used in modern digital computers
(Cooley and Tukey, 1965). A computer program using the Cooley-Tukey
method produces a series of complex Fourier coefficients, and additional
programming isolates the amplitudes and phase relationships of the co-
efficients. Thus it is ideally adapted to the analysis of repeating func-
tions such as the astronomic tides or water waves in the laboratory. The
Blackman-Tukey procedure, on the other hand, involves the auto-correlation
function whose cosine transform gives the spectrum as a function of lag.
This procedure was designed to detect low amplitude signals in a back-
ground of random noise, and is therefore useful for analyzing time series
such as those from complex ocean waves.

The Cooley-Tukey procedure assumes that the record consists of repeat-
ing functions; and, since the data time series is of finite length, the same
care must be taken in its use as with the use of sine and cosine transforms
in the previous programming methods. The amplitudes of the Fourier harmonic
terms do not constitute a power spectrum. However, under certain conditions,
the absolute values (magnitudes) of the complex Fourier coefficients may be
squared to give an approximation of the power spectrum.

The Cooley-Tukey procedure requires that the number of data points in
the time series be some arbitrary power of a small interger. For our pur-
poses it is convenient to use 2^{12} which gives 4096 data points. Since the
last half of the coefficients are complex conjugates of the first half,
2048 data points would result from 4096 data points. It should be noted
that each point obtained from half of the Fourier transform, when squared,
represents only half of the energy density for its particular frequency
band.

Waves generated in the laboratory are of single fundamental frequency
with very little spread of the spectral peak. The energy density estimate
can be calculated with no further processing. The computation of 2048
spectral points is convenient for laboratory data where high resolution
is necessary to isolate the very narrow frequency band of maximum energy
density.

Ocean waves, on the other hand, present a spectrum with random variables
having a standard deviation that is usually large with respect to the band
width of a single estimate. Each calculated coefficient in the Cooley-Tukey
procedure has two degrees of freedom and is nearly independent of its neigh-
bors. Since the fundamental frequency band is usually wide for ocean waves,

the statistical stability is low. Therefore, more statistical stability is achieved with lower resolution and more degrees of freedom for each estimate of energy density if the individual estimates are merged. This is accomplished by programming the computer to combine the calculated values of energy density into groups of, say, eight each, thus forming a new series of 256 terms where each value represents the energy in a much wider frequency band. Since the energy density of a power spectrum uses mean-square amplitudes, the grouping of the Fourier components is the sum of the squares of their members. The phase of each complex Fourier component does not enter into the power spectrum and need not be considered in the grouping process.

The phases of the Fourier coefficients have an arbitrary zero reference depending on the beginning of the time series. However, when two series have the same beginning time and length, the phase differences between the two are real and each phase difference is equivalent to that between two records obtained from cross-spectral analysis using the Blackman-Tukey approach.

The computed complex Fourier coefficients of a single time series provide a useful tool for laboratory studies of wave profile characteristics since they contain information for calculating the phase relationship between the fundamental frequency and each of its harmonics. For example, the wave profile from a train of laboratory-generated waves that are exactly repeating, is completely defined by the amplitudes and relative phase angles of its harmonics.

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by Wayne A. Koontz and Douglas L. Inman
August 1967. 38 pp. incl. 18 illustrations

TECHNICAL MEMORANDUM NO. 21   UNCLASSIFIED

1. Ocean Wave Gages
2. Littoral Transport
3. Littoral Currents
4. Automatic Data
   Processing

I   Title
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III Inman, D. L.

A data acquisition system, using digital techniques, has
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A MULTI-PURPOSE DATA ACQUISITION SYSTEM FOR
INSTRUMENTATION OF THE NEARSHORE ENVIRONMENT
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1. Ocean Wave Gages
2. Littoral Transport
3. Littoral Currents
4. Automatic Data
   Processing

I   Title
II Koontz, W. A.
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A data acquisition system, using digital techniques, has
been designed and tested. Using modern computer techniques,
it acquires and analyzes instantaneous-synoptic measurements
of the nearshore environment. Sensors include: a digital
wave gage with self-contained logic circuitry; a vibrating-
wire transducer to measure bottom pressures; a Savonius
current meter; and a photography technique for estimating
the density of suspended sediments.